

REVEALING THE DARK TEV SKY: THE ATMOSPHERIC CHERENKOV IMAGING TECHNIQUE FOR VERY HIGH ENERGY GAMMA-RAY ASTRONOMY *

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The Atmospheric Cherenkov Imaging Technique has opened up the gamma-ray spectrum from 100 GeV to 50 TeV to astrophysical exploration. The development of the technique (with emphasis on the early days) is described as are the basic principles underlying its application to gamma-ray astronomy. The current generation of arrays of telescopes, in particular, VERITAS is briefly described.

1. Introduction

One of the last frontiers of the gamma-ray sky is that characterized by the distribution of TeV photons. These photons can be detected relatively easily with ground-based detectors (constituting a TeV “window” in the atmosphere); thus the detection of TeV gamma-ray sources did not have to await the availability of space platforms. In practice although the technology was available at an early date, it required the impetus of gamma-ray space astronomy to justify a major effort in a new discipline. Since it concerns the highest energy photons with which it is yet feasible to map the sky, it is of particular interest to high energy astrophysicists. Any source of TeV photons must be associated with a cosmic particle accelerator and of inherent interest to high energy particle physicists as well as students of the cosmic radiation.

To date almost all the observational results in the energy interval 100 GeV - 100 TeV have come from observations using the so-called “Atmospheric Cherenkov Imaging Technique (ACIT).” Although considerable ef-

*This work is respectfully dedicated to the memory of Neil A. Porter (1930-2006), one of the Founding Fathers of Very High Energy Gamma-ray Astronomy.

fort has been applied to the development of alternative techniques, they are more specialized and will not be considered here.

In this historical review of the ACIT, emphasis will be on the early days in which the technique was established; a brief outline of the general principles underlying atmospheric Cherenkov telescopes (ACT) will be given and a description, albeit incomplete, of the ACIT as currently used and the present generation of instruments will be described. More complete accounts can be found elsewhere^{1, 2, 3, 4, 5, 6}.

2. Early History of the Atmospheric Cherenkov Technique

2.1. *Discovery of the Phenomenon*

In the Ph.D. dissertations of students studying the atmospheric Cherenkov phenomenon, the first reference is usually to the 1948 note in the Royal Society report on the study of night-sky light and aurora by the British Nobel Laureate, P.M.S. Blackett⁷; in that note he points out that perhaps 0.01% of the light in the dark night-sky must come from Cherenkov light emitted by cosmic rays and their secondary components as they traverse the atmosphere. Little attention was paid to this prediction (since it seemed unobservable) at the time. Fortunately five years later, when Blackett was visiting the Harwell Air Shower array, he brought his prediction to the attention of two Atomic Energy Research Establishment physicists, Bill Galbraith and John Jelley. After the visit, the idea occurred to them that, while the net flux of Cherenkov light would be impossible to measure, it might just be possible to detect a short light pulse from a cosmic ray air shower which involved some millions of charged particles (Figure 1).

Within a week Galbraith and Jelley had assembled the items necessary to test their hypothesis. A 5 cm diameter photomultiplier tube (PMT) was mounted in the focal plane of a 25 cm parabolic mirror (all housed in a standard-issue Harwell garbage can) and coupled to an amplifier with a state-of-the-art 5 MHz amplifier whose output was displayed on an oscilloscope. They observed oscilloscope triggers from light pulses that exceeded the average noise level of the night-sky background every two minutes. They noted that the pulses disappeared when the garbage can lid was put in place and a padding lamp was adjusted to give the same current in the PMT as was observed from the night-sky⁸. Jelley noted that if the rate had been any lower than that observed they would probably have given up and gone home early!⁹. It is not often that a new phenomenon can be discovered with such simple equipment and in such a short time, but it may

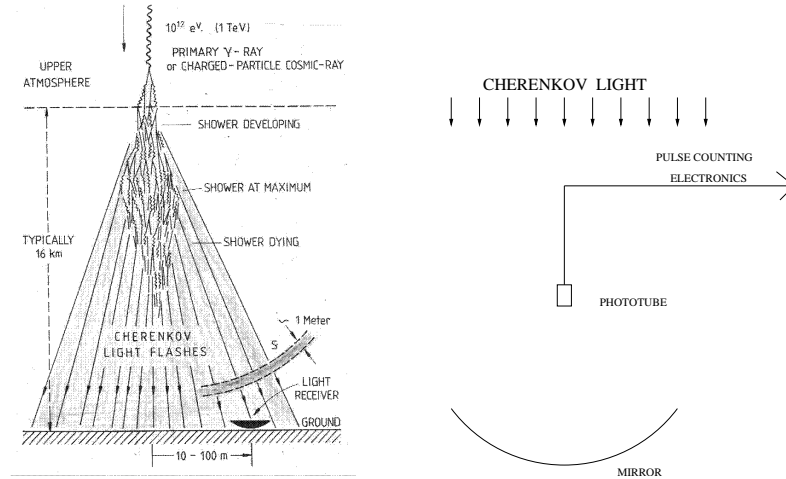


Figure 1. **Left:** Cartoon of the atmospheric Cherenkov shower phenomenon, as drawn by John Jelley in 1993. **Right:** The essential elements of an Atmospheric Cherenkov Detector

also be true that it is not often that one finds experimental physicists with this adventurous spirit! Whereas the modern physicist would not embark on a speculative venture of this nature without extensive simulations, John Jelley had a great suspicion of excessive computation and relied instead on his gut feelings for the inherent physics of the phenomenon; he was seldom wrong!

2.2. The Power of the Technique

With the Harwell air shower array (one of the largest such arrays then in existence) in close proximity, it was easy to show that the light pulses were indeed associated with air showers. In the years that followed, Galbraith and Jelley made a series of experiments in which they determined the basic parameters of the Cherenkov radiation from air showers. The account of these elegant experiments is a must-read for all newcomers to the field^{10, 11}. The basic detector elements of the ACT are extremely simple (Figure 1). It was realized at an early stage that the phenomenon offered the possibility of detecting point sources of cosmic ray air showers with high efficiency. Since charged primaries are rendered isotropic by the intervening interstellar magnetic fields, in practice this meant the detection of point sources of neutral quanta, i.e., gamma-ray photons or perhaps neutrons. The lat-

eral spread of the Cherenkov light from the shower as it strikes the ground is $\approx 100\text{-}200$ m so that even a simple light receiver of modest dimensions has an effective collection area of some tens of thousands of square meters. The fact that the light pulse preserves much of the original direction of the primary particle and that the intensity of light is proportional to the total number of secondary particles, and hence to the energy of the primary, makes the detection technique potentially very powerful.

The prediction by Cocconi¹² of a strong flux of TeV gamma rays from the Crab Nebula precipitated an experiment by the Lebedev Research Institute in the Crimea in 1960-64¹³. Supernova Remnants and Radio Galaxies had recently been identified as sources containing synchrotron-emitting electrons which suggested that they might be gamma-ray sources. A selection of these (including the Crab Nebula) were examined with a ACT system consisting of twelve 1.5 m aperture ex-World War II searchlight mirrors mounted on railway cars at a dark site near the Black Sea (Figure 2). This system did not attempt to discriminate between air showers initiated by gamma rays and those initiated by hadrons. No sources were found but the basic methodology involved in a search for point source anisotropies in the cosmic ray air shower distribution was defined. The technique was refined by John Jelley and Neil Porter in a pioneering British-Irish experiment in the Dublin Mountains in which the candidate source list was expanded to include the recently discovered quasars and magnetic variable stars (with null results¹⁴). This early experiment also used ex-World War II searchlight mirrors on a Bofors gun mounting (continuing the tradition of putting military hardware to good use) (Figure 3). The Smithsonian group led by Giovanni Fazio built the first large optical reflector for gamma-ray astronomy on Mount Hopkins in southern Arizona (Figure 4). This 10 m telescope is still in use after 38 years of service! This again was a first generation device in which the assumption was made that there was no easily measured differences in the light pulses from gamma-ray and hadronic primaries. The motivation for this large increase in mirror area (and decrease in energy threshold) was a refined prediction of a detectable flux of gamma rays from the Crab Nebula based on a Compton-synchrotron model¹⁵.

Although these first generation detection systems were extremely simple and exploited the ease with which gamma rays could be *detected*, they did not provide the means of *identifying* gamma rays among the much more numerous cosmic ray background. Hence, until 1989 when the Crab Nebula was finally detected¹⁶, there was no credible detection of a gamma-ray flux from any cosmic source.



Figure 2. The first ground-based experiment in TeV gamma-ray astronomy which was the Lebedev Institutes's of twelve 1.5 m searchlight mirrors in the Crimea; it had an energy threshold of 1.5 TeV



Figure 3. **Left:** Neil A. Porter (1930-2006) (Photo: D.J.Fegan) **Right:** The second ground-based gamma-ray telescope; the British-Irish experiment at Glencullen, Ireland c. 1964; the telescope consisted of two 90 cm searchlight mirrors on a Bofors gun mounting. The experiment was led by Jelley and Porter.

2.3. Basic Principles

The light signal (in photoelectrons) detected is given by:

$$S = \int_{\lambda_2}^{\lambda_1} k E(\lambda) T(\lambda) \eta(\lambda) A d\lambda$$

where $C(\lambda)$ is the Cherenkov photon flux within the wavelength sensitivity bounds of the PMT, λ_1 and λ_2 , $E(\lambda)$ is the shower Cherenkov emission



Figure 4. The Whipple Observatory 10 m gamma-ray telescope was built in 1968; it is still in operation. It is composed of 250 glass facets, each of focal length 7.3 m.

spectrum (proportional to $1/\lambda^2$), $T(\lambda)$ is the atmospheric transmission and k is a constant which depends on the shower, and the geometry.

The signal must be detected above the fluctuations in the night-sky background during the integration time of the pulse counting system, τ .

The sky noise B is given by:

$$B = \int_{\lambda_2}^{\lambda_1} B(\lambda) \eta(\lambda) \tau A \Omega d\lambda.$$

Hence the signal-to-noise ratio is essentially

$$S/N = S/B^{0.5} = \int_{\lambda_2}^{\lambda_1} C(\lambda) [\eta(\lambda) A / \Omega B(\lambda) \tau]^{1/2} d\lambda.$$

The smallest detectable light pulse is inversely proportional to S/N ; the minimum detectable gamma ray then has an energy threshold, E_T given by $E_T \propto 1/C(\lambda) [B(\lambda) \Omega \tau / \eta(\lambda) A]^{1/2}$

If S = the number of gamma rays detected from a given source in a time, t , and A_γ is the collection area for gamma-ray detection, then $S = F_\gamma(E) A_\gamma t$. The telescope will register a background, B , given by:

$B = F_{cr} A_{cr}(E) \Omega t$, where $A_{cr}(E)$ is the collection area for the detection of cosmic rays of energy E . The cosmic ray background has a power law spectrum:

$F_{cr}(> E) \propto E^{-1.7}$ and if we assume the gamma-ray source has the form: $F_\gamma(> E_\gamma) \propto E_\gamma^{-a_\gamma}$.

Then the standard deviation, $\sigma \propto S/B^{1/2} \propto E^{1.7/2-a_\gamma} [A_\gamma/A_{cr}^{1/2}] t^{1/2}$

The minimum number of standard deviations, σ , for a reliable source detection is generally taken as 5⁶.

3. Early Development of the ACIT

3.1. *Discrimination Methods*

At an early stage it was realized that while the atmospheric Cherenkov technique provided a very easy way of *detecting* gamma rays with simple light detectors, it did not readily provide a method of discriminating the light pulse from gamma-ray air showers from the background of light pulses from the much more numerous cosmic ray showers; thus the *flux sensitivity* was severely limited. Although the hadron showers are isotropic, there is typically a ratio of 1,000-10,000 of cosmic rays to gamma rays recorded by the simple light detectors that were available in the two decades following the Harwell experiments. Once it was apparent that the early, very optimistic, predictions of the strength of the most obvious potential TeV sources were not to be realized, then attention turned to methods of improving the flux sensitivity of the technique. Although superficially very similar, Monte Carlo simulations of shower development and Cherenkov light emission suggested some differences that might be exploited to preferentially select gamma rays.

These differences are listed below:

- Lateral Spread at ground level: the light pool from gamma-ray showers is more uniform than that from cosmic ray showers. This feature is difficult to exploit since it requires numerous light detectors spread over relatively large areas; it has recently been used by the group at the Tata Institute at their Pachmari site¹⁷
- Time Structure: because the cosmic ray component contains penetrating particles (mostly muons) that survive to detector level, the duration of the light pulse can be longer. Many early versions of the ACT, particularly the Haleakala experiment¹⁸, attempted to exploit this feature but it was not to prove very effective,
- Spectral Content: the penetrating component of cosmic ray showers is close to the light detector and its overall Cherenkov light at the detector is less attenuated in the ultraviolet; this feature was used as a discriminant in the early Whipple and Narrabri experiments of Grindlay and his collaborators¹⁹ and in the Crimean

experiments²⁰. It is mostly effective when combined with other discriminants.

- Angular Spread: the image of the light superimposed on the night-sky background has a more regular distribution from gamma-ray showers and is smaller and more uniform. This feature was recognized by Jelley and Porter²¹ but not really exploited until some decades later. This was to prove the most powerful discriminant and to lead to the first successful credible detection of a TeV gamma-ray source¹⁶.

The Cherenkov light image has a finite angular size which can, in principle, be used to refine the arrival direction, and perhaps even to distinguish it from the images of background cosmic rays²². However when a simple telescope with a single light detector (pixel) is used as a gamma-ray detector, this information is lost and the angular resolution is no better than the field of view of the telescope. Because the Cherenkov light images are faint and fast, it is not technically straight-forward to record them. Boley and his collaborators²³ had used an array of photomultipliers at Kitt Peak to study the longitudinal development of large air showers but these were from very energetic primaries. A pioneering effort by Hill and Porter²⁴, using a image intensifier system from a particle experiment, resulted in the first recorded images of Cherenkov light from air showers (Figure 5). These images, although relatively low resolution, demonstrated in a very vivid way the information contained in the Cherenkov image recorded at ground level. The potential advantages of using this detection technique as a means of separating out the gamma-ray component were recognized in a prophetic paper by John Jelley and Neil Porter²¹:

“For a long time it has been appreciated that the image intensifier offers potentialities in this field, and the photography of Cherenkov images against the night-sky is the first step in this direction. Temporarily postponing the technical problems, what are the advantages of this technique? First, with Schmidt optics, it is possible in principle to combine a wide field of view with a high resolution. Secondly, photographs already obtained of the Cherenkov images suggest that their shapes may be used to give detailed information both on the true direction of the shower and also the coordinates of its point of intersection with the ground, in relation to the position of the equipment. The third feature, and it is really the most important one for gamma-ray astronomy of ‘point sources’, is the high angular resolution which may be attained. Though the Cherenkov images are $\approx 2^\circ$ across, and are in general

non-circular in shape, it should be possible to determine a shower direction to $\approx 0.2^\circ$. Thus, we have, for a true point source, a discrimination (by solid angle) against showers from the general-field CR primaries, of ≈ 100 times better than that possible for drift-scans with a photomultiplier system. It might be added here that a stereoscopic technique, with two separated telescopes, would greatly enhance these potentialities.”

However, because of the finite size of the photocathode on the image intensifiers then available, it was only possible to couple them to a relatively small mirrors which meant that only cosmic ray primaries above 100 TeV could be detected. Even then it was necessary to couple these state-of-the-art instruments to a phosphor with decay times of microseconds to allow the image intensifier to be gated and the image recorded photographically. Since this meant that the technique was limited to energies > 100 TeV where the attenuation of the gamma-ray flux by photon-photon pair production in intragalactic space was appreciable, this approach was not pursued at that time. A recent Japanese experiment has revived interest in this technique using the best modern image intensifiers (Sasaki, this workshop).

A novel approach to imaging was that pursued by Grindlay and his colleagues in the seventies¹⁹ in which multiple light detectors separated by distances ≈ 100 m were used to detect the shower maximum associated with gamma-ray showers; this pinpointed the shower arrival direction. The penetrating, mostly muon, component from hadron showers was detected by a second detector and was used as a veto to preferentially select events that were initiated by gamma rays. This “Double Beam” technique was potentially powerful but was difficult to implement with the resources available at the time. Initially the detectors used were 1.5 m searchlight mirrors with single phototubes at their foci; later the 10 m reflector was incorporated into the system with two pixels. The technique received new life when the Narrabri Stellar Interferometer (in Australia) became available. With two large reflectors of 9 m aperture on a circular rail system, (Figure 6) the system, originally built to measure the diameters of bright stars using the intensity interferometer principle, was ideally suited for this technique. Although some detections were reported (the Crab pulsar, the Vela pulsar and Centaurus A)²⁵, they were not confirmed by later, more sensitive, observations. The Double-Beam technique, although ingenious, was not pursued after this although it can be seen as the stalking horse for imaging arrays (see below).

Activity in ground-based gamma-ray astronomy was at a low ebb in the

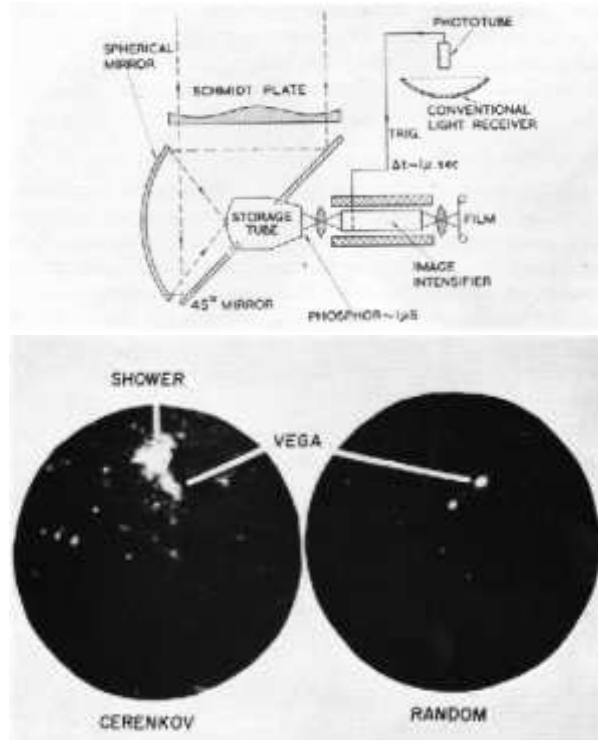


Figure 5. **Top:** Image Intensifier used by Hill and Porter to record the images of cosmic ray air showers²⁴. **Bottom** Images of the night-sky triggered by an ACT (left) and triggered randomly (right). The field of view was $\pm 12.5^\circ$.

seventies. Observations with the Whipple 10 m reflector had moved the energy threshold of the technique close to 100 GeV but this had only produced upper limits on the predicted sources. Smaller telescopes produced tentative detections of several binaries and pulsars but these were always on the edge of statistical credibility and were not subsequently verified (this controversial epoch of TeV gamma-ray astronomy has been reviewed elsewhere^{26, 27}).

3.2. The Power of the Atmospheric Cherenkov Imaging Technique

The concept of using electronic cameras consisting of matrices of phototubes in the focal plane of large reflectors to record the images of the

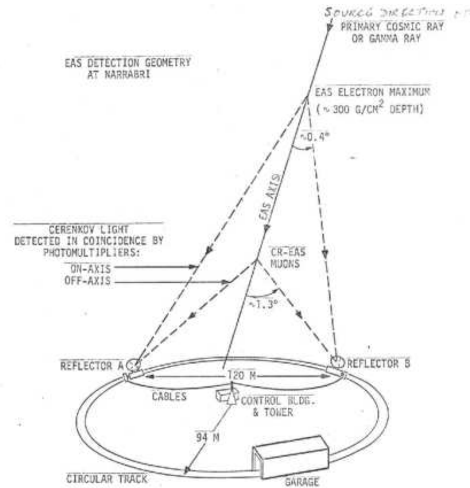


Figure 6. The Double Beam Technique developed by Grindlay in which two reflectors are used, each with two “pixels.” The upper two define the shower maximum and the lower two define the penetrating component and act as a veto to reject hadronic showers.

Cherenkov light from small air showers was first suggested in a paper at a workshop in Frascati, Italy²⁸. Entitled “Gamma-Ray Astronomy from 10-100 GeV: a New Approach” the emphasis was on lowering the energy threshold through the use of two large reflectors separated by 100 m, each equipped with arrays of phototubes in their focal plane. The motivation to go to lower energies came from the prediction from Monte Carlo simulations that the ratio of Cherenkov light from gamma-ray showers to cosmic ray showers of the same energy increases dramatically below 100 GeV. In this paper the physical explanation of this falloff was stated: “In a proton shower most of the Cherenkov light comes from the secondary electromagnetic cascades. Energy comes into these cascades via the production of pions by the primary and the subsequent nucleon cascade. Two thirds of the energy (approximately) goes to charged pions; they can decay to muons or undergo a collision. The latter process is a more efficient method of producing Cherenkov light; since the lifetime against decay is greater a higher energies, the chance of collisions is greater. At lower energies therefore, proportionally more energy comes off in muons whose energy may be below the Cherenkov threshold and hence the low energy showers are deficient in Cherenkov light”. The idea of using an array of phototubes with limited resolution to image the Cherenkov light rather than the high resolution of

ferred by image intensifiers was motivated by the experience of the author using CCD detectors in optical astronomy where the resolution achieved is significantly greater than the scale of the pixels. In the paper there was little emphasis on discrimination of the primaries based on the shapes of the images although it was claimed that there would be a significant improvement in angular resolution (to 0.25°). The use of two reflectors in coincidence was advocated to reduce the predicted muon background.

In this paper²⁸ the basic concept of the Cherenkov light imaging telescope was described; it consisted of an array of PMTs in the focal plane of a large reflector. Although the initial development centered on the use of a single large reflector (the Whipple 10 m reflector, Figure 4), the utility of an array with at least two such cameras was advocated. This has been the model for all subsequent telescopes using the ACIT. In general, in recording the Cherenkov light image from an air shower, the gamma-ray astronomer tries to characterize its nature (gamma-ray or hadron), determines its arrival direction, and gets some estimate of the primary that initiated the air shower. The factors that cause the observed shape and size of the image are many: the nature of the primary particle, its energy and trajectory, the physical processes in the particle cascade (principally pair production and bremsstrahlung in electromagnetic cascades with the addition of pion production in hadron initiated cascades), Coulomb scattering of shower electrons, the effect of geomagnetic deflections of the shower particles, the distance of the point of impact of the shower core from the optic axis, the Cherenkov angle of emission, and the effect of atmospheric absorption⁴. In addition the properties of the imaging system must be completely understood: the reflectivity of the mirrors, the quantum efficiency of the light detectors as a function of wavelength, the time response of the system, and the distortions introduced by the system's optics, cables, electronics and data readout.

Fortunately all of these factors are amenable to calculation or measurement. The physics of the various processes involved in the shower development are well known and Monte Carlo methods can be used to estimate the expected values from particular primaries. However since fluctuations play a major role in such development the expected values cover a range of possibilities and identification must always be a statistical process. It is relatively easy to predict the properties of the gamma-ray initiated showers; it is more difficult to predict the expected properties of the background which is mainly from charged cosmic rays. While every attempt is made to estimate both signal and background, it is usually found that the background

contains some unpleasant surprises; hence although the gamma-ray detection rate can be reliably predicted, the efficiency of the identification of the gamma rays from the more numerous background requires the system to be actually operated in observations of a known source. Since the background is numerous and constant, its properties can be readily modeled from empirical databases of night-sky background events. There is an irreducible background from hadron showers which develop like electromagnetic cascades (most of the energy goes into a π^0 in the first interaction) and from the electromagnetic cascades produced by cosmic electrons (whose fluxes in the range of interest are 0.1 - 0.01% of the hadron flux).

3.3. *The First Source*

When the imaging systems first went into operation it was not immediately obvious how the images should be characterized and discriminated from the background. There were no credible sources and Monte Carlo calculations were still being developed and were untested. The first such calculations available to the Whipple Collaboration indicated that fluctuations might effectively rule out any discrimination and did not encourage the development of sophisticated analysis techniques. The first Whipple camera had 37 pixels, each of 0.25° diameter²⁹. A relatively simple image parameter, *Frac2*, defined as the ratio of the signal in the two brightest pixels to the total light in the image, was developed empirically and led to the first indication of a signal from the Crab Nebula^{30,31}. This simple parameter picked out the compact images expected from electromagnetic cascades but did not provide any information on the arrival direction (other than that it was within the field of view of the detector). However the application of the same selection method on putative signals from the then popular sources, Cygnus X-3 and Hercules X-1, did not improve the detection credibility and initially cast doubt on the effectiveness of *Frac2* as a gamma-ray identifier.

Since the images were roughly elliptical in shape, an attempt was made to quantify the images in terms of their second and third moments³². However this was not applied to gamma-ray identification until Hillas undertook a new series of Monte Carlo calculations³³. These calculations predicted that gamma-rays images could be distinguished from the background of isotropic hadronic images based on two criteria: the difference in the *physics* of the shower development, which led to smaller and better defined ellipses for gamma rays, and the difference in the *geometry* of image formation due to all images coming from a point source on axis having their major axes

intersecting the center of the field of view. Fortunately the first property aids the definition of the second and provides potentially very good angular resolution. Hillas³³ defined a series of parameters which included the second moments (*Width* and *Length*), the parameter *Dist* which measures the distance of the centroid of the image from the optic axis, and *Azwidth* which measures the projected width of the image on the line joining the centroid to the center of the field of view. Later *Alpha*, the angle between this line and the major axis was added as was *Asymmetry*, the third moment. *Azwidth* was particularly simple; it is easy to use and proved to be very effective as it combined discrimination based on image size (physics) and arrival direction (geometry) and led to the first definite detection of a point source of TeV gamma-rays. In general multiple parameter selections were made. The parameters were first defined in Monte Carlo calculations but once the standard candle of the Crab Nebula was established¹⁶, optimization was made on the strong and steady Crab signal to preferentially select gamma rays. This optimization led to an analysis package called Supercuts³⁴, which proved to be extraordinarily robust, and in various forms, was the basis of the data analysis used by the Whipple Collaboration to detect the first AGN^{35, 36, 37, 38, 39}. Other groups have defined different parameters and analysis schemes but the basic methodology is the same.

4. ACT Observatories

4.1. Third Generation Observatories

By 1996 the ACIT was judged to have been very successful and a number of groups made plans for third generation ACTs. The limitation of a single telescope was easily seen from the results obtained using the Whipple telescope and camera⁴⁰. At low trigger thresholds it was impossible to distinguish low energy gamma-ray events from the much more numerous background of partial muon rings (arcs). Despite intense efforts with sophisticated analysis methods, it was clear that the discrimination threshold was a factor of 2-3 above the trigger threshold. Hence although the fundamental threshold was ≈ 200 GeV, the effective gamma-ray threshold was ≈ 400 GeV. Since the muon Cherenkov emission is essentially a local phenomenon, this background is easily eliminated by demanding a coincidence with a second telescope separated from the first by a minimum distance of 50 m²⁸. In fact the HEGRA experiment had already demonstrated⁴¹ the power of an array of small imaging telescopes to improve the angular and energy resolution of the ACIT; at the threshold energies of these telescopes

the muon background was not a problem.

Thus it was apparent that the next generation of the ACIT would involve arrays of reflectors with apertures in excess of 10 m, with better optics, with more sophisticated cameras, and with data acquisition systems capable of handling high rates. Such systems required an investment that was almost an order of magnitude greater than the previous generation of detectors (but the flux sensitivity would be improved by a similar factor). Of necessity the number of people involved in each experiment would be so large (≈ 100) that the new collaborations would be more in line with the numbers of scientists found in particle physics experiments than in typical major astronomical projects.

4.2. *The Power of ACT Arrays*

ACTs arrays can be discussed under the headings of improvements offered in energy threshold, energy resolution, angular resolution and background discrimination. A comprehensive discussion can be found in³. A typical array provides multiple images of a single event as seen in Figure 7.

Energy Threshold: The basic quantities involved in determining the energy threshold of an ACT are given above in Section 2.3 and are fairly obvious: the mirror area should be as large as possible and the light detectors should have the highest possible quantum efficiency. To the first approximation (as demonstrated in¹³) it does not critically depend on how the mirror area is distributed, i.e., a cluster of small telescopes in close proximity operated in coincidence is the same as if their signals are added and is approximately the same as that of a single large telescope of the same total mirror area. Practical considerations tend to dominate: coincidence systems are more stable, the cost of telescopes scales as the Aperture^{2,5}, the relative cost of multiple cameras each on a small telescope versus the cost of a single camera on a large telescope, etc. However the simplest way to get the lowest energy threshold is to go for a single large telescope (although this may introduce other problems).

Angular Resolution: Angular resolution is important not only for reducing the background and identifying a potential source but also for mapping the distribution of gamma rays in the source. Stereoscopic imaging, the simplest form of “array” imaging, offers the immediate advantage of improving the angular resolution. This principle was established with the use of just two telescopes with a separation of ≈ 100 m, i.e., with the two telescopes within the light pool of the Cherenkov light pool, \approx a circle of

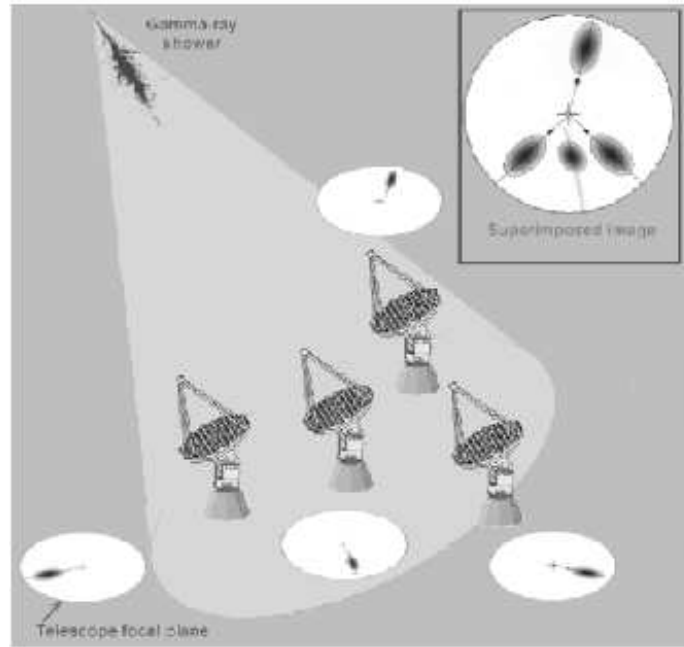


Figure 7. Cartoon showing response of array of four detectors to air shower whose axis is parallel to the optical axes of the telescopes and some 30 m displaced from the center of array. (Figure courtesy of P.Cogan)

diameter 200 m. The greater the separation, the better the angular resolution but increasing the separation beyond 100 m begins to reduce the effective gamma-ray collection area. A simple array of imaging ACTs can provide a source location of $\approx 0.05^\circ$ for a relatively strong source with angular resolution of $\approx 0.1^\circ$ for individual events. This is a factor of two improvement over that for a single telescope. An angular resolution of an arc-min or better appears feasible ultimately.

Background Discrimination: Multiple views of the same air shower from different angles obviously improves the signal-to-noise ratio when the images are combined. However in reducing the background of hadronic events the gain is not as large as might appear at first glance. Hadronic showers which develop like typical showers are easily identified and rejected, even in a single telescope. More subtle are the hadronic events which develop like an electromagnetic cascade (an early interaction channels much of the energy into an electron or gamma ray). Such events cannot be identified no

matter how many views are provided on the cascade development. Similarly the cascades initiated by cosmic electrons are an irreducible background. However the array approach does completely remove the background from single local muons and the improved angular resolution narrows the acceptable arrival directions.

Energy Resolution; The Cherenkov light emitted from the electromagnetic cascade is to a first approximation proportional to the energy of the initiating gamma ray and thus can be considered a calorimetric component. However with a single ACT there is no precise information as to the impact parameter of the shower axis at ground level. Since the intensity of the Cherenkov light is a function of distance from the shower axis, the lack of information on this parameter is the limiting factor in determining the energy of the gamma ray. The energy resolution of a single imaging ACT is $\approx 30\text{-}40\%$. With an array the impact parameter can be determined to ≈ 10 m and the energy resolution, in principle, can be reduced to 10%.

4.3. *The Third Generation Arrays*

This third generation of ACTs has seen the formation of four large collaborations formed to build arrays of large telescopes: a largely German-Spanish collaboration that is building two 17 m telescopes on La Palma in the Canary islands (MAGIC)⁴²; an Irish-British-Canadian-USA collaboration that is building an array of four 12 m telescopes in Arizona (VERITAS)⁴³; an Australian-Japanese collaboration that has built four 10 m telescopes in Australia (CANGAROO-III)⁴⁴; a largely European collaboration that has built an array of four 12 m telescopes in Namibia (HESS)⁴⁵ and plans to add a fifth telescope of 28 m aperture at the center of the array. The fact that two of the arrays are in each hemisphere is somewhat fortuitous but ensures that there will be good coverage of the entire sky and that all observations can be independently verified. Three of arrays are discussed elsewhere at this workshop; here the VERITAS observatory will be briefly described.

The sensitivity of these new arrays is probably not dissimilar; HESS and MAGIC has demonstrated what can be achieved in the actual detection of known and new sources. With the second generation of ACTs (Whipple, HEGRA), it was possible to detect a source that was 5% of the Crab Nebula in 100 hours of observation. With HESS this is reduced to one hour and in principle in 100 hours it should be possible to detect a source as weak as 0.5% of the Crab. HESS has also demonstrated an energy resolution of

10% and an angular resolution of an arc-min.

5. VERITAS

The configuration chosen for VERITAS was a filled hexagon of side 80 m; in the first phase funding was available for only four telescopes so the hexagon has three non-adjacent vertices missing⁴³. The four telescopes and cameras of VERITAS are identical and are now at an advanced state of construction. The first two telescopes and cameras were installed at a temporary site (the Whipple Observatory Basecamp at an elevation of 1.3 km) and saw first “gamma-ray light” in February, 2005 (Figure 8). The properties of the first telescope have been described elsewhere^{46, 47}.

Telescope: The VERITAS telescopes are of the Davies-Cotton optical design with 12 m aperture and 12 m focal length. The mechanical structure consists of an altitude-azimuth positioner and a tubular steel optical support structure (OSS). The design is closely modeled on the existing Whipple 10 m optical reflector but with the added feature of a mechanical bypass of the upper quadrapode arm which transfers the load of the camera to the counterweight support. Completion of the first two telescopes has allowed the properties and sensitivities of the individual telescopes to be measured⁴⁷.

The 350 individual mirror facets on each telescope are hexagonal, each with an area of 0.322 m², providing a total mirror area of ~ 110 m². They are made from glass, slumped and polished; the glass facets are aluminized and anodized at the VERITAS optical coating laboratory on-site. The reflectivity of the anodized coating is typically $> 90\%$ at 320 nm. Each facet has a 24 m radius of curvature. They are located on a three point mounting on the spherical front surface (radius 12 m) of the OSS. The point spread function (PSF) at the position of Polaris (elevation 31°) was measured to be 0.06° FWHM; with bias alignment it is anticipated that this PSF will be achieved over most of the operating range of VERITAS.

Camera: The VERITAS cameras are closely modeled on those used previously by the group at the Whipple telescope but incorporate much more advanced triggering, electronics readout and data acquisition systems³¹. The instrumentation in the focal plane is a 499 element photomultiplier tube (PMT) camera, with 0.15° angular spacing giving a field-of-view of 3.5° . The camera is shown in Figure 8. The PMTs are Photonis XP2970/02 with a quantum efficiency $> 20\%$ at 300 nm, currently operated at a gain of $\sim 2 \times 10^5$. The PMT signals are amplified by high bandwidth preamplifiers



Figure 8. **Left:** The first two VERITAS Telescopes. **Right:** The 499 pixel PMT camera.

integrated into the PMT base mounts. The signals are sent via ~ 50 m of RG59 stranded cable to the telescope trigger and data acquisition electronics, at which point the observed pulse for an input delta function has a rise time (10% to 90%) of 3.3 ns and a width of 6.5 ns.

The PMT signals are digitized using custom-built VME boards housing Flash ADCs with 2 ns sampling and a memory depth of $32\mu\text{s}$. The trigger system is multi-level. At the telescope each channel is equipped with a programmable constant fraction discriminator (CFD) for each PMT, the output of which is passed to a pattern recognition trigger system which is programmed to recognize triggers resembling true compact Cherenkov light flashes. Individual telescope triggers are delayed and combined to form an overall array trigger. The FADCs permit the telescopes to operate at a lower threshold than would otherwise have been possible⁴⁷.

Future Program: The scientific program will concentrate on the study of extragalactic objects including AGN, radio galaxies, starburst galaxies and clusters, compact galactic objects including pulsars, binaries and microquasars, extended objects such as supernovae remnants, unidentified sources discovered in future space missions, and signatures of dark matter in the center of galaxies. A sky survey will be undertaken and the study of gamma-ray bursts will have high priority.

Acknowledgments: Over the past 40 years ground-based gamma-ray astronomy at the Smithsonian's Whipple Observatory has been supported by times by the Smithsonian Astrophysical Observatory, the U.S. Department of Energy, the National Science Foundation and NASA. D.J Fegan is thanked for helpful comments on the manuscript.

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